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DEVELOPMENT OF NOZZLE FOR PSLV BOOSTER

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Abstract

The development and fabrication of nozzle for 2.8 m dia booster motor of Polar Satellite Launch Vehicle (PSLV) is described. The nozzle is a convergent-divergent type designed with 24 ports for secondary injection thrust vector control (SITVC). It is the third largest nozzle for solid rocket motor in the world with a throat dia of 836 mm and overall length of 3640 mm.
The nozzle is comprised of three segments. Carbon phenolic ablative liners are used in the convergent, throat and SITVC regions, while silica phenolic liner is used in divergent aft end. Metallic back up made of 15CDV6 steel is used in all the segments. The nozzle segments are fabricated by bonding hardware and liners with epoxy adhesive followed by finish machining the inside contour and interfaces. The nozzle in assembled condition weighs 4 tonnes.
The ablative liners are processed using state-of-the-art technologies involving tape winding, moulding, hydroclave curing and machining. The process technology was evolved after development trials covering subscale liner winding, hydroclave curing of thick laminates and material evaluation for throat region in subscale motor tests.
The booster motor has 128 t HTPB based propellant and two static tests have been conducted successfully. During the tests nozzle was actuated by TVC system through injection of strontium perchlorate to get a side thrust of 20 tonnes and the performance of the nozzle has been satisfactory. The successful tests have demonstrated the adequacy of ablative liners processing and nozzle fabrication technologies.

1. Introduction

Vikram Sarabhai Space Centre (VSSC) has successfully designed and developed solid propellant motors upto 1 metre dia for ISRO's launch vehicle and sounding rocket programmes.[1] The operational nozzles have been conventional convergent-divergent type. They are made of carbon phenolic & silica phenolic ablative liners with structural back up and graphite is used at throat region. Nozzle with SITVC system has also been developed for Satellite Launch Vehicle (SLV) and Augmented Satellite Launch Vehicle (ASLV) programmes. A submerged type nozzle with flexible bearing for thrust vector control is also under advanced stage of development for Polar Satellite Launch Vehicle (PSLV) third stage motor. The development of nozzle for PSLV booster motor, besides its massive size, involved following new elements as compared to its forerunners.

i) Carbon phenolic throat

ii) Tape wound liners with 60° ply orientation and hydroclave curing to impart erosion resistance and consistant performance.

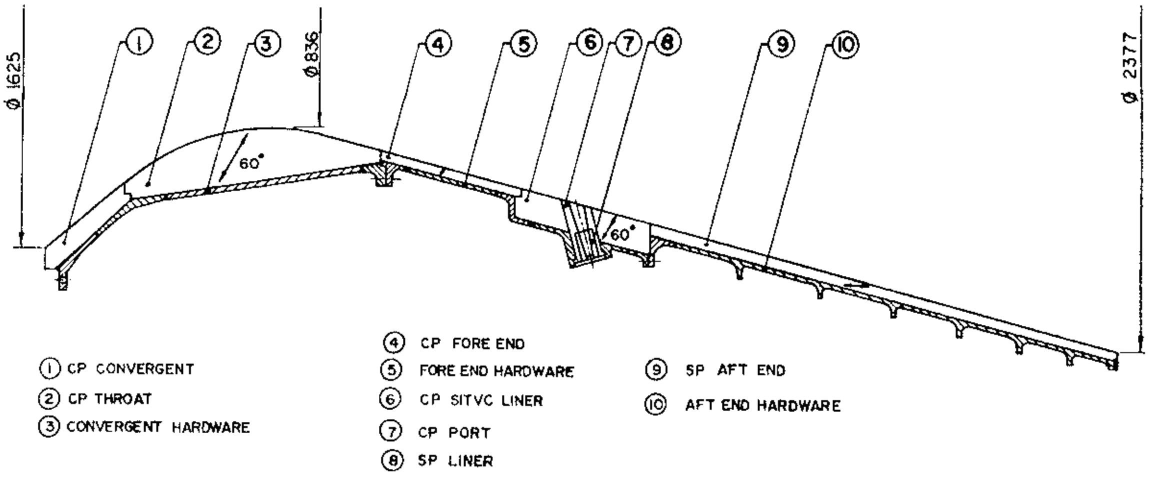
Material evaluation, design and fabrication of process toolings and process trials on subscale liners for the booster nozzle were initiated in 1984. The fabrication of metallic hardware and ablative components commenced during 1986. Two static tests of the motors were conducted successfully in October 1989 and March 1991.

2. Nozzle description

The nozzle is designed considering following functional requirements:

Design MEOP, Mpa : 5.88
Action time, sec. : 100
Max. thrust deflection: 3°
Expansion ratio : 8

The nozzle has nominal throat dia 836 mm, 1625 mm inlet dia and 2377 mm dia at exit as shown in Fig.1. The metallic hardware is made of 15CDV6 steel in three segments. The convergent segment has convergent and throat liners made of carbon phenolic. While convergent liner



FIG·1· NOZZLE

is made of rosette lay up, throat liner is wound with 60° orientation to nozzle axis.

Fore end and SITVC liners are also made of carbon phenolic with 60° orientation and are housed in divergent fore end metallic segment. All these carbon phenolic liners are hydroclave cured. For thrust vector control, 24 ports are provided at 35% location from throat plane. The port liners are made of carbon phenolic bonded with silica phenolic inner sleeve.

The aft end segment is made of silica phenolic liner with 0° orientation and bonded with metallic back up. The liner is vacuum bag cured in oven. The segments are attached with high tensile bolts and 'O' rings.

3. Ablative liner development

The nozzles developed in-house so far had carbon phenolic liners in erosion-prone regions of convergent and divergent fore end. Graphite was used as throat material. The design of carbon phenolic liners for booster nozzle called for generation of data on thermo-mechanical properties.

3.1 Property measurement:

The properties of carbon phenolic laminates cured at 4 MPa pressure were measured at elevated temperatures and are shown in Table 1. The test specimens were charred by controlled

Table 1

ELEVATED TEMPERATURE PROPERTIES OF CARBON PHENOLIC LAMINATES

	PROPERTY		TEMPERATURE, K				
			RT	550	800	1600	2500
1.	Density, g/cc		1.45	1.42	1.26	1.13	1.10
2.	Thermal conductivity, W/mK	(WP)	0.06	1.45	1.72	3.46	16.3
		(AP)	0.3	1.13	0.82	2.1	5.1
3.	Specific heat, Cal/g K		0.26	0.35	0.425	0.53	0.575
4.	Thermal expansion, %	(WP)	0.005	0.07	0.06	0.31	0.7
		(AP)	0.01	0.045	0.12	0.465	1.2
5.	Tensile strength, MPa	(WP)	115	108	55	31	29
6.	Shear strength (ILSS), MPa		12	10.5	2.7	4.6	4.3

heating and cooling under inert atmosphere and soaked for 30 minutes at test temperatures.

3.2 Throat material evaluation

Carbon phenolic material was evaluated for application in throat region in two subscale motors of 300 mm and 1 m dia. The throat liner for 300 mm dia motor was made with 90° orientation to nozzle axis due to small size of liner and throat erosion observed was 0.12 mm/sec.

The 1 m dia motor test had carbon phenolic throat tape wound with 60° orientation and autoclave cured at 1 Mpa pressure. The test parameters and liner erosion data are shown in Table 2. In both the inserts density of the material was maintained at 1.35 g/cc.

Table 2

SUBSCALE MOTOR TEST
WITH CP NOZZLE THROAT

Motor dia, m	1
Propellant type	HTPB
Propellant wt., t	9
Burn time, sec.	35
Throat dia, mm	398
Rate of erosion at throat, mm/s	0.15
Char thickness at throat, mm	8.5

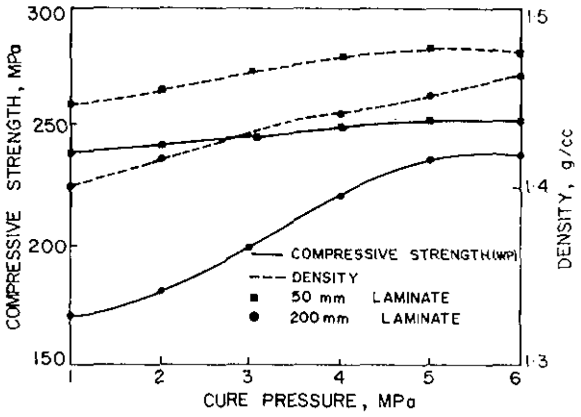
3.3 Process development

The carbon phenolic liners for booster nozzle required use of bias cut/pattern cut tapes due to 60° orientation. Also the liners being of large thickness called for high compaction at winding stage to reduce ply wrinkling during hydroclave curing. Hence winding trials were conducted on subscale liners of 290 mm ID and 420 mm OD to achieve 'as wrapped' density of 85% and following parameters were frozen for prepregs and winding.

Prepregs:
Resin content : 40-45%
Volatile content : 8% Max

Winding:
Tape heating temp. : 105°C
Roller pressure : 80 Kg/cm width

In view of the large thickness and low permissible erosion of carbon phenolic liners, they were proposed to be cured in hydroclave. Fixing the cure pressure levels was of concern. While certain minimum pressure is essential to obtain optimum density, higher pressure poses risk of vacuum bag failure and also ply wrinkling. Hence a study was conducted to see the effect of cure pressure levels on properties of thick carbon phenolic laminates. Laminates of 50 - 200 mm thickness were cured at 1 - 6 MPa pressure and properties obtained are shown in Fig.2.



FIG·2· PROPERTIES OF THICK CP LAMINATES

Curing of massive rosette laid up convergent liner posed another problem. Due to its low density in laid up condition, high compaction was expected while curing, posing risk of vacuum bag failure. Also, plies adjacent to mandrel tend to separate due to large thermal expansion of mandrel and enough pressure has to be ensured while curing to avoid delamination in this zone.

Considering above aspects, cure cycle was established for subscale liner of 450 mm ID and 900 mm OD. The cycle involved liner consolidation upto 95% density under 1.5 MPa pressure at 90° C followed by rebagging and curing at 150°C under 3 MPa pressure. About 40% compaction was observed in the cured liner in comparison to the laid up stage.

4. Nozzle fabrication

The fabrication of metallic hardware for the nozzle and toolings for liner fabrication were subcontracted. The nozzle hardware was of rolled and welded construction made from 15CDV6 steel. The acceptance tests covered radiography, dye penetrant tests on weld joints and dimensional inspection.

The toolings fabricated were of three types:

- Mandrels for tape winding, moulding & curing
- Fixtures for machining of liners and nozzle subassemblies
- Fixtures for bonding of liners with hardware.

The fabrication of ablative liners, subassembly machining, and nozzle assembly were carried out in-house. The nozzle fabrication involved following steps:

1. Pre-impregnation
2. Tape winding and moulding
3. Curing
4. Liner machining
5. Acceptance testing
6. Subassembly bonding and machining
7. Nozzle assembly

4.1 Pre-impregnation:

The impregnation of carbon cloth and silica cloth was carried out in impregnation plant which has provision for cutting prepreg tapes along warp direction. Prepreg specifications were adopted from subscale trials.

4.2 Tape winding and moulding

Tape winding of liners was carried out in a horizontal winding machine. The machine has tape winding set up mounted on bed which can be swivelled horizontally to suit mandrel taper. The winding set up comprises tape feeding unit, hot air blower and a hydraulically actuated pressure roller for tape lay up at 0°-60° ply orientation.

Throat, divergent fore end and SITVC liners were wound using carbon phenolic prepreg tapes maintaining 60° orientation to mandrel axis. Each winding mandrel had 60° conical ring welded at end. The winding operation was carried out by laying up prepreg tape on face of the ring. Subsequently, tapes were progressively wound upto full length by application of heat and pressure ensuring tape inside edge to touch mandrel surface. The tape winding parameters were adopted from the subscale development trials. Circular segment cut tapes and 45° bias cut tapes having 100 - 385 mm width were used in these liners. The fore end liner was wound by forming of bias cut tape to 60° orientation using taper rollers in winding machine. For winding of throat and SITVC liners the `tape width/dia' ratio was too high for tape forming. Hence circular segment cut tapes were used for these liners.

The divergent aft end liner was wound using warp cut silica phenolic prepreg tapes maintaining the orientation parallel to mandrel axis.

The convergent liner was moulded by hand lay up and involved following steps:

- Finalising outer dimensions of lay up
- Selection of ply length
- Ply development
- Rosette lay up

The envelope of the lay up was finalised considering 40% compaction of liner during hydroclave curing. A lay up using plies of short length offers steep ply angle normal to mandrel surface and high erosion resistance. But it poses risk of ply separation due to mandrel expansion during curing. For the present lay up, large plies of 780 mm length were used. The ply pattern was developed subsequently to obtain desired liner dimensions and the plies were laid up over the mandrel in rosette pattern. The liner had thickness varying from 150 mm to 450 mm along the length and 2900 plies were used in the lay up.

4.3 Curing

Due to large size and high cost of the liners, a safe approach was adopted based on subscale liner experience for hydroclave curing, in order to avoid rejection. Following were the salient features adopted for curing the liners.

- Monitor liner temperature at different locations and tune cure cycle during curing.
- Maintain low heating and cooling rates to restrict temperature gradient in liner within $1^{\circ}C$ per cm thickness
- Pressure application in steps to avoid abrupt movement and possible rupture of vacuum bag.
- Cure at minimum pressure levels essential to obtain defect free liners.
- Pre-consolidation at $90^{\circ}C$ for thick liners.

For hydroclave curing, the tape wound and moulded liners were wrapped with separator film, breathers and sealed in silicone rubber bags. The mandrels had ports for vacuum, thermocouple connection and clamping rings for sealing bag at flanged ends. During curing, liner temperature was monitored at 6 - 9 locations using redundant thermocouples. The convergent, throat, divergent fore end and SITVC liners were hydroclave cured at 2 - 4 MPa pressure depending on liner thickness. The cure duration for the liners varied from 35 hours to 80 hours. Cure cycle adopted for divergent fore end liner is shown in Fig.3. The throat liner was the heaviest carbon phenolic component cured weighing 1 tonne.

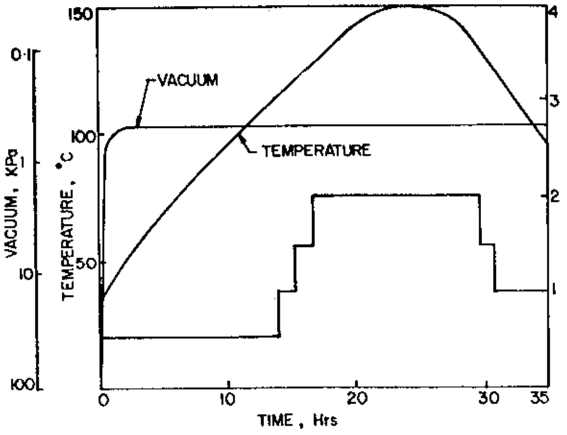


FIG-3. HYDROCLAVE CURE CYCLE FOR CP FORE END LINER

The silica phenolic divergent aft end liner was vacuum bagged and cured under ambient pressure in a hot air circulating oven.

The liners for the SITVC ports were made of carbon phenolic bonded with silica phenolic inner liner. They were moulded using 12mm sq. prepreg chops and cured using band heaters wrapped over the mould under hydraulic pressure.

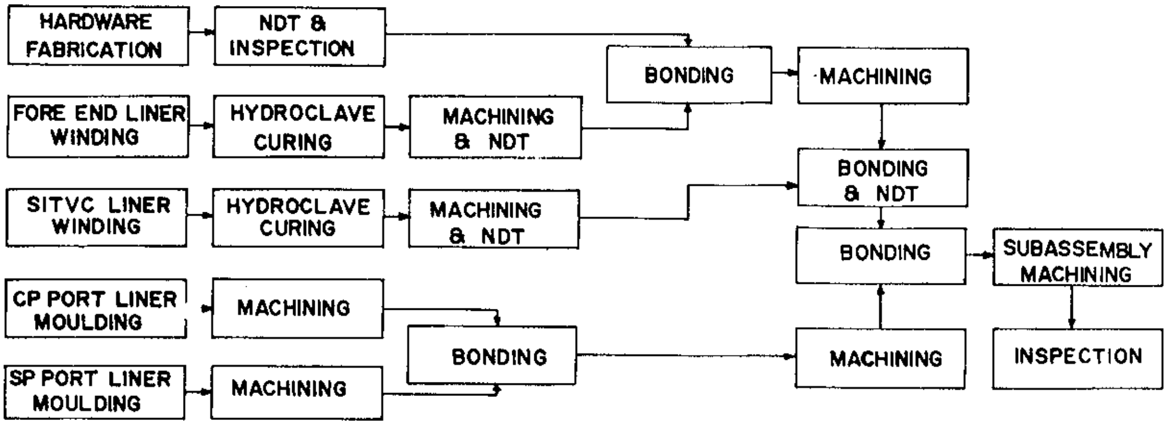
In making the ablative liners, 8,500 sq.m. of carbon cloth and 1500 sq.m. of silica cloth were consumed.

4.4 Liner Machining

After curing, the liners were extracted from the mandrels and mating surfaces with the hardware were finish machined. Machining was carried out in a three-axis CNC vertical turning mill using diamond and carbide tipped tools. Dust generated during machining was extracted continuously by vacuum suction.

4.5 Liner Acceptance Tests

All the liners were radiographed for acceptance. Surface defects were scanned by acetone penetration tests and visual inspection. Additionally, density was measured from the end rings machined from each of the liners.



FIG· 4 : FABRICATION OF DIVERGENT FORE END SUBASSEMBLY

Carbon phenolic liners had density 1.35 to 1.45 g/cc and density of silica phenolic liner was 1.65 g/cc.

4.6 Segment subassembly

The accepted liners were bonded with the metallic hardware using room temperature curing two-part epoxy resin system. The mating surfaces of the components were brushed with the resin and components were positioned in place using bonding fixture till completion of resin curing. Bonding was inspected by ultrasonic testing. Nozzle inside contour and segment interfaces were finish machined for each subassembly. Dimensions were inspected in 3-axis coordinate measuring machine and precision micrometer.

Fabrication time for each of the three subassemblies varied from 10 to 15 weeks. The divergent fore end segment subassembly involved maximum number of operations as shown in Fig.4.

4.7 Nozzle assembly

The segment subassemblies were positioned on saddles horizontally. The nozzle was then assembled keeping 'O' rings in place and fastening the joints using torque wrenches. A sealant putty was also used while assembly to fill the gap between the segments and served as a redundant seal.

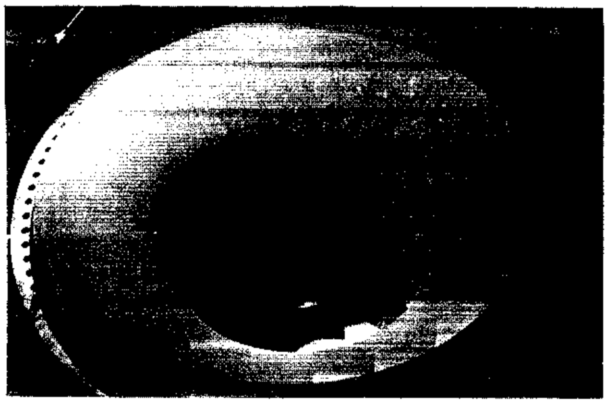


FIG. 5 : NOZZLE CONVERGENT

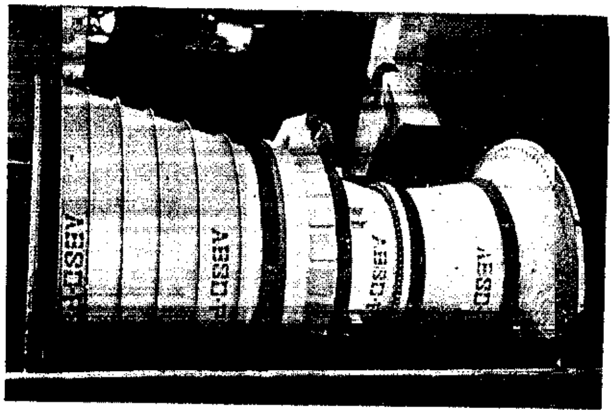


FIG. 6 : NOZZLE ASSEMBLY

5. Motor static testing

First static test of motor was conducted on 21st Oct 1989 and second test on 23rd March 1991. Both the tests were successful and performance of the nozzles were satisfactory and consistant. The test conditions and post test data for the first static tested nozzle are shown in Table 3.

Table 3

MOTOR TEST PARAMETERS

Motor dia, m	: 2.8
Propellant type	: HTPB
Propellant wt., t	: 128
Action time, sec.	: 100
Ave. chamber pressure, MPa	: 3.75
Max. thrust, kN	: 4622

NOZZLE PERFORMANCE

Zone	Location A/A_t	Erosion rate (mm/s)	Char thickness (mm)
Convergent	-2.0	0.23	18
Throat	1.0	0.23	18
SITVC	2.5	0.04	17
Aft end	6.0	0.05	6.5

6. Conclusion

The development of nozzle for PSLV booster has been successfully completed. The satisfactory and consistant performance of the nozzle has been demonstrated in two successive successful static tests of booster motor. The motor is the biggest developed in the country and will serve as work horse for PSLV flights and proposed Geo-synchronous Satellite Launch Vehicle (GSLV) programmes.

7. Acknowledgements

The development of nozzle was possible due to dedicated team work of colleagues in Ablative Systems Division. Support facilities in Composites Group and other various divisions in Vikram Sarabhai Space Centre have contributed in timely realisation of nozzle. The motor development and testing was co-ordinated by Solid Motors Project. The static tests were conducted at SHAR Centre. Authors wish to acknowledge Mr. Rajaram Nagappa, Dy.Director for his support and Dr. S.C. Gupta, Director VSSC for permitting publication of this paper.

Reference

[1] Nagappa, R and Kurup,M.R., "Development of HTPB propellant system for ISRO's Motors" AIAA paper 90-2331, July 1990.